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Muonium and Positronium Physics * [redacted]

J.M. BAILEY and V. W. HUGHES [redacted]
Yale University, New Haven, Conn. U.S.A.

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1. Introduction

Quantum electrodynamics is our best understood and most precisely verified theory. Both the electron and the muon appear to be Dirac particles with conventional electrodynamic coupling. Electrons and muons partake in no strong interactions but they do have weak interactions. Precise measurements on these particles, both when free and when in the bound hydrogen-like systems of muonium (μ^+e^-) and positronium (e^+e^-) have been vital to the establishment and verification of the theory of quantum electrodynamics. Such measurements are also useful for obtaining information about certain of the fundamental atomic constants, in particular the fine structure constant α. For the interpretation of these measurements only the electromagnetic interactions need be considered because the weak interactions are small by comparison. The effects of strongly interacting particles on higher order radiative corrections become important(1) only to an accuracy well beyond present experimental precision. In contrast, the effect of strong interactions on the hydrogen atom, which contains a proton, is considerably greater than the uncertainties of present-day experiments.

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Many experiments, in particular measurements of the electron g-value g_e,[2] the Lamb-shift,[3] and positronium hyperfine structure,[4] show that electrons are "Dirac-particles" (i.e., are completely described by Quantum Electrodynamics). An accurate measurement of the muon g-value,[5] a comparison of high-energy electron-proton[6] and muon-proton[7] scattering, and muon-pair photoproduction[8] show that the muon is also a Dirac particle.

Muonium and positronium are the atoms which we feel we understand best. The two other atoms antimuonium ($\mu^- e^+$) and the bimuon ($\mu^+ \mu^-$) should similarly be well understood, but they are difficult to form and have not yet been observed. Recent theoretical speculations[9] of great interest in the field of weak interactions have considered the possibility of a four-fermion interaction which will take muonium directly into antimuonium. Because of the importance of this possible coupling, we shall consider the properties of antimuonium.

Muonium[10] is in most respects a light hydrogen isotope, very similar to ordinary hydrogen. Positronium is quite different from hydrogen; its reduced mass of $m_e/2$ makes its gross structure differ from that of hydrogen by a factor of two, and the radiative corrections to its energy levels are quite different from those of hydrogen. Furthermore in atomic collisions it behaves very differently from hydrogen. Both of these rare atoms have short lifetimes. The muon which forms the nucleus of muonium decays in 2×10^{-6} sec to give a fast positron with energy up to 50 MeV, and with an angular distribution $I(\theta) \propto 1 - (\cos\theta)/3$ referred to the spin direction of the muon. The whole positronium atom annihilates; the triplet state decays in 10^{-7} sec to three gamma rays with a continuous energy distribution up to 511 keV, while the singlet state decays in 10^{-10} sec to two gamma rays of energy exactly 511 keV. In experiments on muonium one usually measures the angular distribution of the decay positrons, and in experiments on positronium one measures the energy spectrum, angular distribution or time distribution of the annihilation gamma rays.

Experiments(4,10) require a source of polarized positive muons (commonly a synchrocyclotron) for muonium and a positron emitter (such as Na^{22}) for positronium; these provide particles with energies of the order of a few MeV. The particles form muonium or positronium by charge capture when they are stopped in fairly dense media, which we try to choose so as to give reasonably large numbers of muonium (or positronium) atoms; evidently we should try to choose media in which muons form muonium and nothing else and similarly for positrons. When our wanted atom has been formed, it will undergo collisions with the atoms of the surrounding medium, which will perturb it, combine with it chemically, or even break it up; obviously our medium should be inert to minimize these problems. Experiments such as hyperfine structure measurements require exposing the system to a static magnetic field and also to a microwave field in order to induce transitions between atomic sublevels; we must understand all the effects of these fields before we can confidently interpret our results.

In experiments on muonium and positronium we must thus consider many types of atomic collisions. We are not primarily concerned with the details of energy loss of fast positive muons and positrons, since even if muonium and positronium form they rapidly break up again in collisions, but below about 100 eV we must consider five types of muon-atom collisions: elastic collisions with and without spin-flip, muonium formation, atom-excitation (and ionization), and muon-molecule formation. Then we must also consider muonium-other-atom collisions of six types; elastic collisions with and without spin-flip, muonium-excitation, muonium-ionization, muonium-atom attachment, and atom excitation (and ionization). For positrons and positronium we must consider all the above collision processes and in addition positron annihilation.

Experiments with positrons and positive muons stopping in various media have given considerable information on these atomic processes; conversely the theory of these processes, together with experimental results on hydrogen in various media, have given information of great value for the interpretation of the muonium and positronium results.

Since the muon and positron (and electron) are well understood Dirac particles, and since atomic collisions involve only the electrodynamic coupling, the basic quantum theory of atomic collisions involving the muon, muonium, positron and positronium is known and the prediction of observed cross sections should be limited only by calculational complexities. Because the muon mass is intermediate between that of the electron and the proton and because the charge of the positron is opposite to that of the electron, studies of collision cross sections involving these particles are useful to the further development of the theory of atomic collisions. We shall examine in some detail atomic collisions of muons and muonium, and of positrons and positronium from both a theoretical and an experimental viewpoint.

2. Muon- and Muonium-Atom Collisions

We shall consider here only positive muons, which behave like light protons in atomic processes - for example, they tend to capture electrons. In contrast, negative muons behave like heavy electrons - for example, they tend to be captured into orbits about atomic nuclei. The similarity of positive muons to protons holds also after the formation of muonium, which behaves like a light isotope of hydrogen in its collisions with other atoms.

Theoretical treatments of muon- (or proton-) atom collisions generally consider H and He atoms, although some Hartree wave-functions of heavier atoms have been used. We may hope that calculations on He will reproduce the main features of processes in argon, which has been used in most muonium experiments. High energy p-He collisions have been treated by the Born approximation[11] (although this may be invalid[12]) and by the impulse approximation.[13] But as mentioned above, low-energy collisions are most important, and here the method of perturbed stationary states[14] seems most promising.

A calculation of muonium formation by this last method[15] shows features like those occurring with hydrogen: the cross-section is small below an energy (termed "activation energy" by Massey and Smith[14]) of about 40 eV (which is considerably greater than the threshold of the process, 11 eV), but above this energy it rises fairly steeply to values of the order of $10^{-16}cm^2$ at 100 eV, as shown in Figure 1.

FIGURE 1.

The high-energy calculations indicate that for energies of a few keV the cross-section is again of order 10^{-16} cm^2, decreasing at higher energies. Experiments on charge capture by protons[16] in inert gases show good qualitative agreement with these results, but quantitative agreement is poor. Experiments on muonium[17,10] indicate that in argon more than 50 per cent of the muons form muonium and retain their polarization throughout. A search for optical transitions when muons are stopped in various media could give information on capture into excited states.

In considering collisions of muonium (and H) atoms with neighboring atoms we again restrict our discussion to inert buffer gases; He is simplest for calculations. For hyperfine-structure experiments the most important effect is the shift in the hfs caused by the change in the electron wave-function of muonium during elastic collisions. Calculations[18] of this require consideration of the diatomic muonium-He system. To first order one finds the fractional change in the hfs interval $\Delta\nu$ to be proportional to the density of the particular buffer gas (but varying, in magnitude and sign, with different buffer gases). This is in excellent agreement with optical pumping experimental results[19] on the three hydrogen isotopes in several different buffer gases; the three isotopes have widely differing values of $\Delta\nu$ but the fractional shifts $d(\ln \Delta\nu)/dp$ are very closely equal (to within 2%) and are in good agreement also with the experimental value found for muonium[10] (which is rather less accurately known), which is shown in Figure 2.

FIGURE 2

In conjunction with these experiments on the hydrogen isotopes, measurements[10] on the effect of adding various amounts of different gases to the argon used in muonium experiments and measurements of the depolarization of muons stopping in other media have given information on molecule-formation and spin-exchange collisions of hydrogen-like atoms, and on spin-flip collisions of the muon.

The formation of anti-muonium in vacuo may proceed[9] at such a rate that the decay will occur with a branching ratio of about 10^{-5} from anti-muonium. However since the world around us is not charge symmetric, muonium and anti-muonium atoms in several atmospheres of buffer gas will not have precisely the same energy and the branching ratio will be more like 10^{-9}. So the experiment will be difficult. Theoretical consideration of the diatomic system He-anti-muonium is necessary to obtain estimates of this branching ratio and also to decide what experimental method is most promising. The properties of anti-muonium are quite different from those of muonium in collision processes; electron-positron annihilation is very important in this and similar[20] systems. Calculations[21] indicate that in collisions of anti-muonium with atoms of the surrounding medium, the μ^- will form a mesic atom, whose x-ray transitions will provide a possible means of detecting this process.

3. Positron- and Positronium-Collisions

Collisions of positrons and positronium with other atoms form a class by themselves; results obtained from calculations or experiments on other particles and atoms are completely unreliable as a guide. (This contrasts with muons and muonium, which are very similar to protons and hydrogen.) The theory of positron-atom collisions[22,23] is different from that of electron-atom collisions both because the positron is attracted to atomic electrons and is not subject to an exclusion principle, and because of the new processes of electron-positron annihilation and of positronium-formation among the possible inelastic collisions. Moreover positronium is different from other atoms in that its center of mass is not a heavy nucleus, so that some standard methods (e.g., the Born-Oppenheimer approximation) are inapplicable.

High-energy positron collisions[22,24,25] may be treated by Born or impulse approximations. As for muonium, low-energy collisions are important, and since positrons are so light, we may expect the Born approximation to be more valid at energies of the order of 30 volts than was the case for muons (inapplicability of Born approximation is a question of velocity, not energy); the distorted-wave approximation has also[24] been used. As with muonium, the real problem with positronium formation in a dense buffer gas is the question of ultimate formation (for which we must understand both formation and breakup), and a Monte Carlo method[26] has been used to investigate this; it is worth noting that the short lifetime of singlet positronium may result in the positronium annihilating before it has a chance to break up by impact ionization. The presence of a static electric field[27] causes the velocities of positrons in the buffer gas to have a Druyvesteyn distribution rather than a Maxwellian one, and positronium formation is enhanced; this is because positrons with thermal energies cannot form positronium, but in a field they diffuse and have a higher energy which allows positronium formation. Since the positron is so light this effect is quite large, and moreover it occurs also with electric fields at microwave frequencies (which considerably complicates experiments[4] on positronium). The elastic positron-atom cross-section is important for understanding the diffusion process.

Collisions of positronium with buffer gas atoms should produce a density shift (as for muonium), and the possibility of annihilation with electrons of the target atoms; moreover spin-exchange collisions can change triplet to singlet (short-lived) positronium, and hence quench triplet decays.

Experimental results are in fairly good agreement with theoretical predictions. Formation in an electric field[25,28,29] behaves as predicted, and values of cross-sections for various processes have been obtained. In particular the cross-section for elastic scattering of positrons by a given atom is much smaller[30] than the value for electrons. A search for the optical transition 2p - 1s indicates that very little positronium is formed in the 2p state. The addition of a small amount of NO to the inert gas in which positronium is formed quenches triplet decays via spin-exchange collisions. A new measurement[31] of the hfs of positronium is now being carried out, and should yield results of much higher accuracy than previously.

4. Conclusion

Experiments on muonium and positronium give the most unambiguous and precise values of the fundamental constant α, and also give valuable information about many atomic collision processes.

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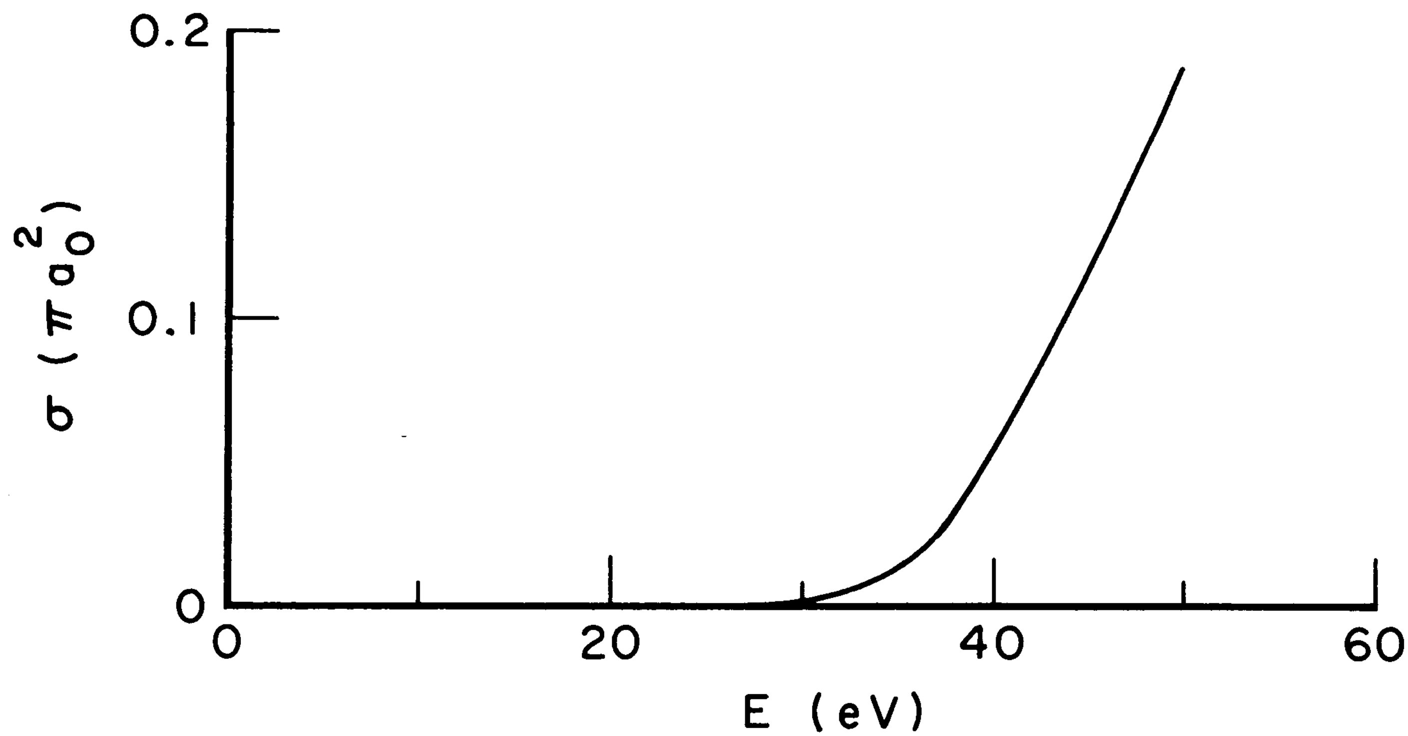
Figure 1. Calculated cross-section for formation of muonium in the 1S state as a function of muon energy.

Figure 2. Ground-state hfs interval of muonium as a function of buffer gas pressure, showing the density-shift effect; preliminary experimental results.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0.1
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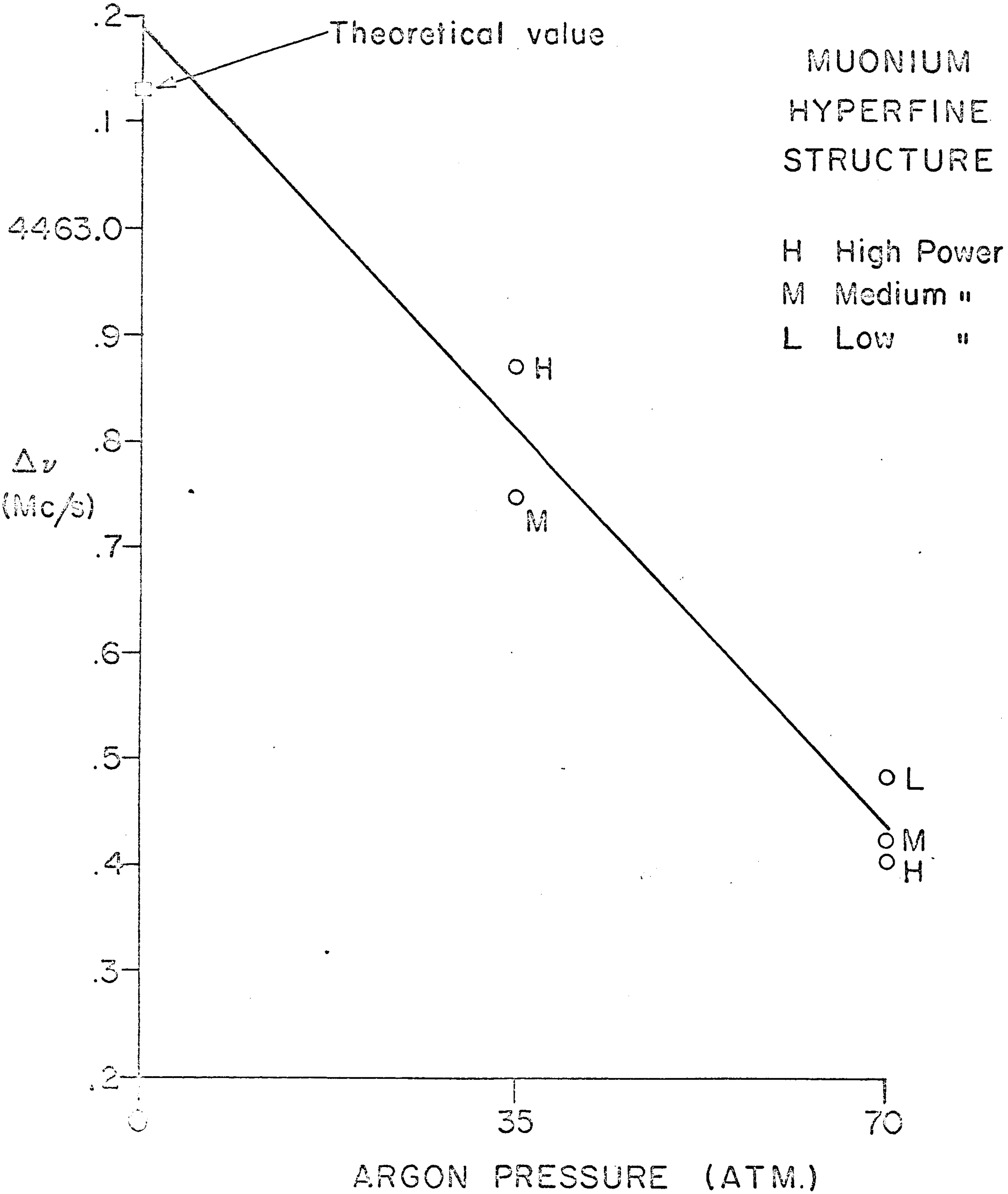
σ (πa₀²)
0
20
40
60
E (eV)



Theoretical value
MUONIUM
HYPERFINE
STRUCTURE
H High Power
M Medium "
L Low "
.2
.1
4463.0
.9
.8
.7
.6
.5
.4
.3
.2
$\Delta\nu$
(Mc/s)
H
M
L
M
H
0
35
70
ARGON PRESSURE (ATM.)